APPENDIX F

AQUIFER TESTS

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F1.0 AQUIFER TESTS

Aquifer tests are conducted to determine the hydraulic properties of an aquifer system such as hydraulic conductivity, transmissivity, and storativity. These properties are useful in determining fate and transport of contaminant plumes and in designing effective groundwater remediation systems.

Since pumping tests and slug tests evaluate a much larger volume of the aquifer, they are the most commonly accepted methods for determining representative aquifer properties at sites with groundwater monitoring wells. Other aquifer evaluation methods may be used following prior Department approval.

It is essential to have a basic understanding of groundwater hydraulics and the effects an aquifer test will have on the aquifer system. It is not the intent of this section to give a detailed explanation of every aquifer test and its limitations, but rather to review basic terminology and provide the fundamental concepts for conducting an aquifer test. A general discussion of pumping tests and slug tests is presented in this section. The reader is directed to the references in this section for more detailed procedures in conducting aquifer tests.

Determine Site Constraints

During the site investigation, soil data should be collected to determine the site's geologic and hydrologic characteristics. The site investigation shall be performed in accordance with RECAP Appendix B, as well as the guidelines established in the latest versions of the LDEQ and LDOTD *Construction of Geotechnical Boreholes and Groundwater Monitoring Systems Handbook* and *Louisiana Administrative Code (LAC) 56 Part I Water Wells.*

When installing groundwater monitoring wells, consideration of well placement should be given to the vertical and horizontal delineation of the contaminant, as well as for well placement in conducting an aquifer test. One should consider well design (i.e., partially penetrating wells, fully penetrating wells, etc.) and well location (i.e., recharge zones, lateral discontinuities in an aquifer, etc.) which may place additional complexities in evaluating the aquifer test data.

Existing groundwater monitoring wells may be used to conduct the aquifer test provided the wells were constructed in accordance with the latest versions of the LDEQ and LDOTD *Construction of Geotechnical Boreholes and Groundwater Monitoring Systems Handbook* and *Louisiana Administrative Code (LAC) 56 Part I Water Wells*.

F2.0 AQUIFER TYPES

The type of aquifer must be determined as unconfined or confined. An ***unconfined*** aquifer (or water table aquifer) is defined as an aquifer that is bound by a free surface under atmospheric pressure at the upper boundary of the water bearing unit. In an unconfined aquifer, the water level in wells or piezometers is free to rise and fall under the influence of atmospheric pressure and may typically have a static level below the upper stratigraphic boundary of the aquifer.

A ***confined*** aquifer (or artesian aquifer or pressure aquifer) is defined as an aquifer that is bounded by impervious or semipervious strata. In a confined aquifer, the water level in wells or piezometers may rise due to pressure head to a static level above the upper stratigraphic boundary of the aquifer.

An **aquitard** is a less permeable formation that transmits water very slowly from one aquifer to another. An **aquifer system** consists of the aquifer and any aquitards.

The **hydraulic head**, h, is defined as the total mechanical energy per unit weight of water. Hydraulic head has the units of length and is given by the relationship:

$$\mathbf{h = z + h_p}$$

where:

h - hydraulic head (ft.)
z - elevation head (ft.)
h_p - pressure head (ft.)

In a confined aquifer, the pressure head of groundwater at the top of the aquifer is always greater than zero. The hydraulic head in a confined aquifer is typically characterized as the vertical distance by which the static water level in a well or piezometer exceeds the upper stratigraphic boundary of the aquifer.

Since an unconfined aquifer is free to rise and fall in response to atmospheric pressure, the pressure head is zero.

F3.0 AQUIFER PROPERTIES

Hydraulic Conductivity (K)

Hydraulic conductivity is a measure of the capacity of a porous medium to transmit water. It is defined as the volume of water that will move in a unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow. The dimensions of hydraulic conductivity are length per time. Hydraulic conductivity is governed by the size and the shape of the pores, the effectiveness of the interconnection between pores, roughness of mineral particles, degree of soil saturation, and the physical properties of the fluid.

Saturated Aquifer Thickness (b)

The **saturated aquifer thickness** may be determined from published reference boring/well logs or field data. The saturated thickness of the aquifer has the dimensions of length [L]. For confined units, the saturated thickness will correspond to the thickness of the aquifer. For unconfined units, the saturated thickness represents the vertical distance from the mean annual static water level elevation to the base of the aquifer. For multi-layered or interconnected units, the saturated thickness of each sub-unit should be determined separately.

If the **saturated aquifer thickness** is unknown, an estimated value can often be obtained from many published references or well logs. This information may be available through the United States Geological Survey (USGS), the Louisiana Geological Survey (LGS), or the Louisiana Department of Natural Resources (LDNR). If a boring is advanced into an aquifer of unknown thickness, the estimated saturated aquifer thickness shall be set equal to the maximum penetrated thickness of the water-bearing unit (as determined from boring logs) plus 10 feet subject to Department approval. If a boring is not advanced, the default aquifer thickness shall be set equal to 10 feet.

Transmissivity (T)

Transmissivity is defined as the rate at which water can be transmitted through a unit vertical section of aquifer extending through the full saturated thickness under a unit hydraulic head.

$$\mathbf{T = K * b}$$

where:

T - transmissivity (ft^2/day)
K - hydraulic conductivity (ft/day)
b - saturated aquifer thickness (ft)

Specific Yield (S_y)

Specific yield is defined as the percent ratio of the volume of water that an unconfined aquifer will yield by gravity to the unit volume of the unconfined aquifer. As the water level falls in an unconfined aquifer, water is drained from the pore spaces. Specific yield is given by the relationship:

$$S_y = \frac{\text{Vol. of water an unconfined aquifer will yield by gravity}}{\text{Unit Vol. of the unconfined aquifer}}$$

The specific yields of unconfined aquifers generally range from 0.01 to 0.30 depending on the type of porous materials.

Specific Storage (S_s)

Specific storage is the volume of water that a unit volume of aquifer releases from storage under a unit decline in hydraulic head. The dimensions for specific storage are 1/length or length^{-1}.

Storativity (S)

Storativity, or coefficient of storage, is a dimensionless coefficient defined as the volume of water that a permeable unit will release from storage per unit surface area per unit change in head. In an unconfined unit, the level of saturation rises or falls with changes in the amount of water in storage due to specific yield. Storativity for an unconfined aquifer is expressed by the following relationship:

$$\mathbf{S = S_y + S_s\, b}$$

where:

S - storativity (dimensionless)
S_y - specific yield (%)
S_s - specific storage (ft^{-1})
b - saturated aquifer thickness (ft)

In a confined aquifer, the aquifer remains saturated during pumping and specific yield is zero. The storativity for a confined aquifer is given by the relationship:

$$\mathbf{S = S_s\, b}$$

where:

S - storativity (dimensionless)
S_s - specific storage (ft^{-1})
b - saturated aquifer thickness (ft)

Values for storativity in unconfined aquifers generally range from 0.02-0.3 and from 0.005 to 0.00005 for unconfined aquifers.

Porosity (n)

Porosity is defined as the percent ratio of the volume of voids in a rock or sediment to the total volume of the rock or sediment. The voids in the rock or sediment include all pore spaces that are liquid or air filled and not available to conduct flow because of discontinuities. The void spaces that are connected and available to conduct flow are termed **effective porosity**, n_e.

F4.0 DETERMINING AQUIFER PROPERTIES BY DIRECT MEASUREMENT

One criterion for determining groundwater classification is to estimate the maximum sustainable well yield of an aquifer. **Maximum sustainable well yield** is defined as the maximum sustainable volume of water that a well will discharge over a given period of time. It is has the dimensions of volume per time. All water wells used to estimate maximum sustainable yield shall be designed, constructed and developed in accordance with the latest versions of the LDEQ and LDOTD *Construction of Geotechnical Boreholes and Groundwater Monitoring Systems Handbook* and *Louisiana Administrative Code (LAC) 56 Part I Water Wells*.

For sites with groundwater monitoring wells, aquifer properties such as hydraulic conductivity, transmissivity, and storativity can be measured by two common methods, pumping tests and slug tests, which are discussed below.

F5.0 CONCEPTUAL DESIGN OF A PUMPING TEST

F5.1 Determine Appropriate Conceptual Model

The single most important step in the analysis of aquifer test data is the selection of an appropriate conceptual model. Each conceptual model has a set of assumptions about the geometry and hydraulic behavior which one must determine appropriate for the study site. Based on the observed site constraints, a conceptual model or models must be selected to determine the aquifer properties.

The conceptual model is usually based on geologic and hydrologic data generated during the site investigation, design of monitoring wells, the drawdown data obtained during the aquifer test, and the set of assumptions for the study site.

A list of several conceptual models and references are provided in Table F-1 to direct the reader to a more detailed description of the mathematical models and assumptions. Other conceptual models may be used following Department approval.

F5.2 Estimation of Well Yield

The development of the Theis equation (1935) takes into consideration the effect of pumping time on well yield. The Theis equation is based on assumptions such as the pumping well being 100 percent efficient, the water table is horizontal without slope, the aquifer formation is uniform in thickness and infinite in areal extent, the hydraulic conductivity is the same in all directions, groundwater flow is laminar, etc. Cooper and Jacob (1946) observed that if the pumping test is of sufficient duration or the distance from the pumping well to the observation well is sufficiently small, the exponential integral function of the Theis equation can be replaced with a logarithmic term simplifying the evaluation of well hydraulics. Applying some assumptions of storativity, drawdown, distance from pumping well to observation well and pumping duration to the Cooper and Jacob modification of the Theis nonequilibrium well equation, an estimate of well yield can be obtained. The estimated well yield equations are presented in Figure 1.

F6.0 PUMPING TESTS

In a pumping test, groundwater is extracted from a pumping well with water level measurements observed in the pumping well and in one or more observation wells. Pumping tests can be performed within an aquifer to collect information relative to the aquifer in which the pumped well and observation wells are located. In addition, a **stress pumping test** can be performed to determine the transmissivity or degree of leakage between an unconfined aquifer and a deeper leaky confined aquifer. In this test, the pumped well is located in the lower aquifer while the observation wells are located in the overlying aquifer which is separated by a less permeable aquitard.

The difference in hydraulic head in the pumped well or in the observation wells at the start of the test and at some time after the test begins is referred to as **drawdown**, **s**, and has the dimension of length. The distance from the center of the pumping well to the point where drawdown is zero is referred to as the **radius of influence**, **R**, and has the dimension of length. The depressed area of influence around the pumped well is referred to as a **cone of depression** because it is shaped like an inverted cone. As pumping continues, drawdown increases and the cone of depression expands. If the pumping rate is constant and sustained over a sufficient time period, the drawdown and radius of influence become constant referred to as an **equilibrium** or **steady state** condition. Non-steady state conditions are referred to as **transient** flow. The rate of change in hydraulic head per unit of distance of flow in a given direction is the **hydraulic gradient**, **i**, and has the dimensions of length per length [L/L]. Groundwater velocities are highest near the pumped well due to the increase in hydraulic gradient, and decrease radially away from the well.

There are basically two types of pumping tests: a constant-rate pumping test and a step-drawdown pumping test. A **constant-rate pumping test** is performed by pumping the well at a constant rate for the duration of the test. It is most often used to obtain aquifer properties such as transmissivity and storativity as well as specific capacity of the well. Depending on the type of aquifer, the well is pumped at a constant rate for an extended period of time. Typically, the test is conducted for 24 hours in a confined aquifer and 72 hours in an unconfined aquifer; however, the duration may be shortened if equilibrium conditions are observed. It is recommended the pumped well or discharge well should be a minimum of 4 inch outside diameter and the well screen fully penetrating the aquifer, (i.e., the well screen is fully saturated). Spacing of observation wells are id dependent on the type of aquifer being evaluated. During this time, periodic drawdown measurements are taken in the pumped well and observation wells. Upon completion of the test, the recovery data is often collected to check the results against the data collected from the actual test. The aquifer performance can be predicted by plotting the drawdown data versus the time the data was collected and evaluating the transmissivity and storage coefficients.

Another type of pumping test is the **step-drawdown pumping test** in which the pumping rate is increased in steps at regular intervals. This test is usually conducted for 24 hours in either typ of aquifer; however, the duration may be shortened if equilibrium conditions are observed. It is also recommended the pumped well or discharge well should be a minimum of 4 inch outside diameter and the well screen fully penetrating the aquifer, (i.e., the well screen is fully saturated)._Again, the drawdown data is collected in both the pumped well and the observation wells and plotted versus time to obtain the transmissivity and storage coefficients. This test is primarily used to determine the reduction in specific capacity with increasing yields.

F7.0 SLUG TESTS

A **slug test** involves either injecting or withdrawing a known volume of water into or out of a well and immediately measuring the rate at which the water level falls or rises back to static conditions. For wells that are partially penetrating, the withdrawal slug test is recommended to overcome the affects of the filter pack. For fully penetrating wells where the well screen remains completely saturated, either the injection or withdrawal slug test is appropriate.
The flow of water into or out of the well is governed by the formation characteristics. The water level in the well is measured prior to and immediately after the abrupt injection or withdrawal of water. The subsequent water levels are measured until the water level returns to static or equilibrium conditions. In aquifers with high hydraulic conductivity, recovery may occur so rapidly that the use of a pressure transducer is required. The pressure transducer measures the pressure changes in the well as the water level changes and stores the data in the recording equipment. The data is plotted as a change in water level versus time from which aquifer properties such as hydraulic conductivity, transmissivity, and storage coefficients are estimated. When averaging a number of hydraulic conductivity results from the same water bearing unit, the geometric mean of the hydraulic conductivities shall be used. If more than one water veering unit is being evaluated, a hydraulic conductivity must be obtained from each respective water bearing unit.

It is recommended that a minimum of three slug tests be conducted from at least three different groundwater monitoring wells within the same water bearing unit.

Wells used for slug testing should have a minimum diameter of 2 inches. Additionally, pressure transducers and data loggers shall be used in all slug tests.

Several methods used to evaluate data from slug tests are presented in Table F-2. Other conceptual models may be used following Department approval.

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Table F-1
Conceptual Pumping Test Models

Aquifer Type	Flow Condition	Aquitard Leakage	Aquitard Storage	Well Storage	Partial Well Penetration	Anisotropic Properties	References
Confined	Equilibrium	No	No	No	No	No	Thiem (1906)
Unconfined	Equilibrium	No	No	No	No	No	Thiem (1906)
Confined	Transient	No	No	No	No	No	Theis (1935)
Confined	Transient	Yes	No	No	No	No	Hantush & Jacob (1955)
Confined	Transient	Yes	Yes	No	No	No	Hantush (1964)
Confined	Transient	No	No	No	Yes	Yes	Hantush (1964)
Confined	Transient	Yes	No	No	Yes	Yes	Hantush (1964)
Confined	Transient	No	No	Yes	No	No	Papadopulos & Cooper (1967)
Confined	Transient	Yes	No	Yes	No	No	Lai & Su (1974)
Confined	Transient	Yes	Yes	No	No	No	Boulton & Streltsova (1977)
Confined	Transient	No	No	No	No	Yes	Papadopulos (1965)
Confined to Unconfined	Transient	No	No	No	No	No	Moench & Prickett (1972)
Unconfined	Transient	No	No	No	No	Yes	Neuman (1972)
Unconfined	Transient	No	No	No	Yes	Yes	Neuman (1974)
Unconfined	Transient	No	No	Yes	Yes	Yes	Boulton & Streltsova (1976)
Unconfined	Transient	Yes	Yes	No	Yes	Yes	Boulton & Streltsova (1975)

Table F- 2

Conceptual Slug Test Models

Aquifer Type	Flow Condition	Aquitard Leakage	Aquitard Storage	Partial Penetration	Anisotropic Properties	References
Confined	Transient	No	No	Yes	Yes	Hvorslev (1951)
Confined	Transient	No	No	No	No	Cooper et al. (1967)
Unconfined or Leaky	Transient	Yes	No	Yes	No	Bouwer & Rice (1976)

(After Dawson and Istok, 1991)

Figure F-1
Estimation of Well Yield

Reference: Driscoll, F.G., *Groundwater and Wells*, 1986, 2nd ed., Johnson Division, St. Paul, Minnesota.

The estimated well yield equations are derived from the Cooper and Jacob (1946) modification to the Theis (1935) nonequilibrium well equation. The Cooper and Jacob modification using English engineering units is given as:

$$s = \frac{264Q}{T}\log\frac{0.3\,T\ t}{r^2\ S}$$

where:

s = drawdown at a distance (r) from the pumping well, feet
Q = yield from pumping well, gpm
T = transmissivity, gpd/ft
t = time of pumping, days
r = distance from pumping well to observation well where drawdown is measured, feet
S = storativity, dimensionless

The estimated well yield equations are derived using some assumptions and logarithmic functions. The estimated well yield equations and assumptions are given as:

<u>Confined Aquifer</u>

$$Q = \frac{60\ h_c\ K\ b}{9.3 + \log(K\ b)}$$

<u>Unconfined Aquifer</u>

$$Q = \frac{16\ K\ b^2}{6.3 + \log(K\ b)}$$

where:

Q = estimated well yield, gpm
h_c = confining head above the upper stratigraphic boundary of the aquifer, feet
K = hydraulic conductivity of the aquifer media, cm/sec
b = saturated aquifer thickness, feet

Assumptions:

$s = 0.75\ h_c$ feet (confined aquifer)
$s = 0.2\ b$ feet (unconfined aquifer)
$t = 7$ days
$r = 0.5$ feet
$S = 1.0E\text{-}04$ (confined)
$S = 1.0E\text{-}01$ (unconfined)